

N90-21082

**ASCIE: AN INTEGRATED EXPERIMENT TO STUDY CSI IN LARGE SEGMENTED
OPTICAL SYSTEMS**

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3rd Annual NASA/DoD CSI Conference
Jan 29 - Feb 2, 1989

LARGE SEGMENTED REFLECTOR SYSTEMS

The use of a segmented primary mirror is one of the major design concepts for the new generation of large ground and space-based telescopes. The W. M. Keck Ten-Meter Telescope (TMT), whose structural model is shown on Fig. 1, or NASA's planned Large Deployable Reflector (LDR) are typical examples of this approach. In a segmented reflector the mechanical rigidity and geometric accuracy are supplied solely by the support structure. Imperfections in the manufacturing process, deformations due to gravity loads, thermal gradients, slewing and tracking dynamics, and structural vibrations make it imperative that the positions of the segments be actively controlled. For example, the TMT segment alignment system requires 162 sensors, 108 actuators, and a special control system to align its 36 segments.

An important characteristic of such systems is that the supporting truss is very light (even for ground-based telescopes like the TMT), thus very flexible, with usually low natural damping. As a result, interactions between the segment alignment control system and the structural dynamics are expected to occur.

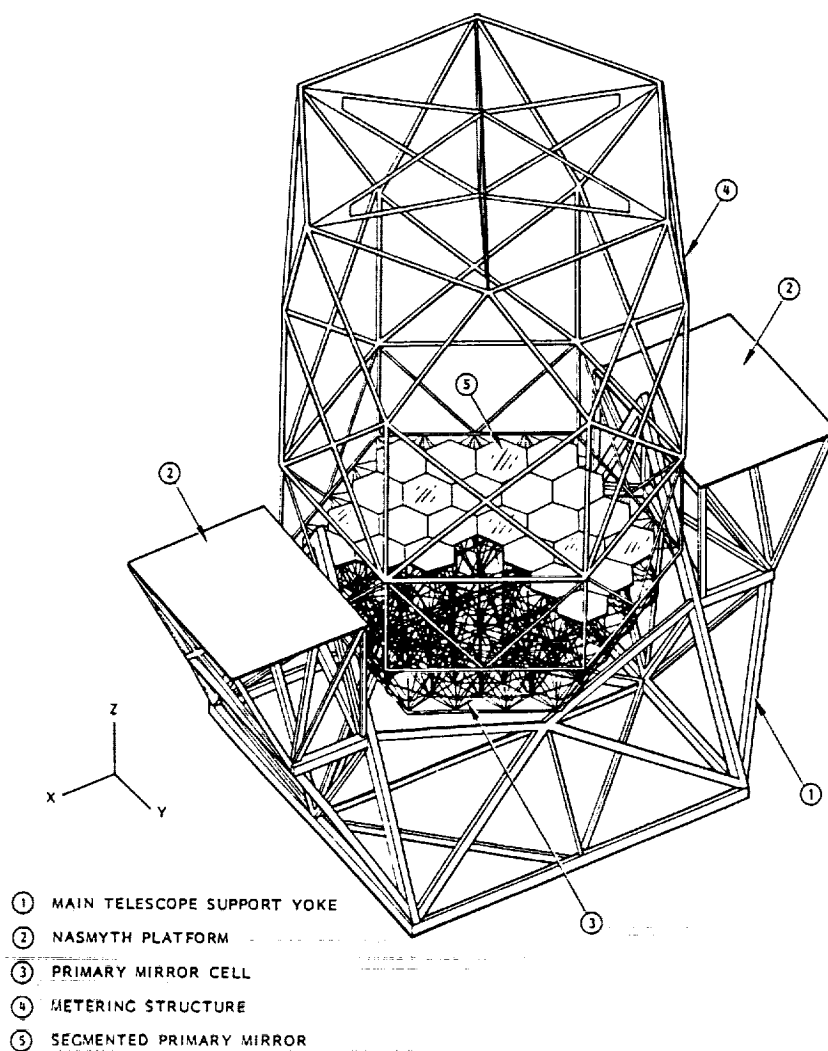


Figure 1

MOTIVATION FOR THE DEVELOPMENT OF AN INTEGRATED EXPERIMENT

The interaction between the control system actuators and sensors with the dynamics of the support structure seriously limits the performance of the system. A recent analytical study done by Lockheed [refs 1, 2 and 3] of the TMT that modelled the full structure, actuator and sensor set, and control system operation showed that control system stability was seriously affected by dynamic coupling between the segments through the support structure. Tests performed on a single segment and support cell conducted at the Lawrence Berkeley Laboratory failed to predict this phenomenon because they did not account for the effects of collective motion and coupling in the full system. While analysis can be very effective in predicting major behavior, there are numerous practical problems that must be solved and tested with real hardware. Moreover, the design and implementation of a multi-actuator, multi-sensor control system for large flexible segmented reflectors (LFSR) has never been experimentally validated. There was thus a need to develop a test bed that could support strong interdisciplinary studies to develop and validate the emerging LFSR technology.

ASCIE OBJECTIVES

A unique ground experiment called the Advanced Structures/Controls Integrated Experiment (ASCIE) has been conceived and developed as a means of performing meaningful laboratory experiments for the design, implementation, and validation of control strategies for large flexible systems with distributed optical elements, and in particular for large segmented telescopes. The ASCIE test bed has been designed to support a number of interdisciplinary studies that address major technical challenges of LFSRs. One of the immediate objectives of this project concerns the study of structures/controls interaction in LFSRs. However the scope of ASCIE is of a more general nature. Topics such as structural control (e.g. active damping, vibration suppression, disturbance alleviation) or pointing and slewing techniques for LFSRs will also be addressed using the ASCIE system.

The near-term goal for the ASCIE is to demonstrate in the laboratory a fully operating TMT-like segment alignment control system with a level of performance comparable to that required for a real telescope. This study will provide a means to investigate the CSI phenomenon in a real structure and compare it to analytical predictions. Longer term goals include substantial improvements in bandwidth and disturbance rejection through the use of advanced control techniques.

ASCIE FEATURES

The ASCIE structure shown in Fig. 2 consists of a 2-meter, 7-segment, actively controlled primary mirror supported by a light, flexible truss structure. The optical system emulates that of an $f/1.25$ Cassegrain telescope and utilizes an actively controlled secondary mirror. The six peripheral segments are controlled in three degrees of freedom using specially developed precision actuators. Segment alignment is obtained through the use of edge sensors whose signals are processed by the control system which then generates the commands for the actuators. One of the unique features of the ASCIE is its optical scoring and calibration system which eliminates the requirement that the segments have real optical surfaces. Small optical flats combined with a special faceted secondary mirror reflect laser beams onto an array of linear position-sensing photodetectors.

The active control of the secondary mirror is necessary to provide correct initial alignment of the primary segments. It will also be used to improve image stability and to simulate a chopping secondary, a feature found in all infrared astronomical telescopes [Refs 4 and 5]. Controlling the secondary mirror to stabilize the image at the focal plane is another example of a non-collocated system where CSI pays an important role [Ref 6].

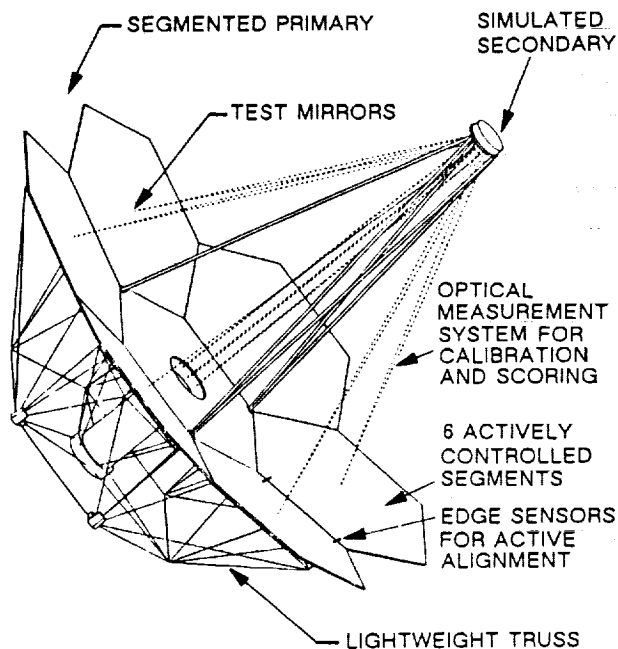
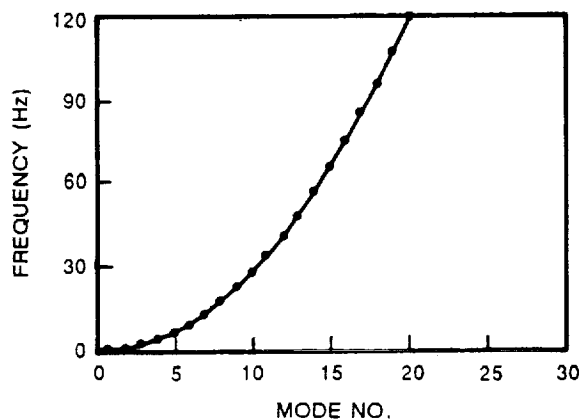
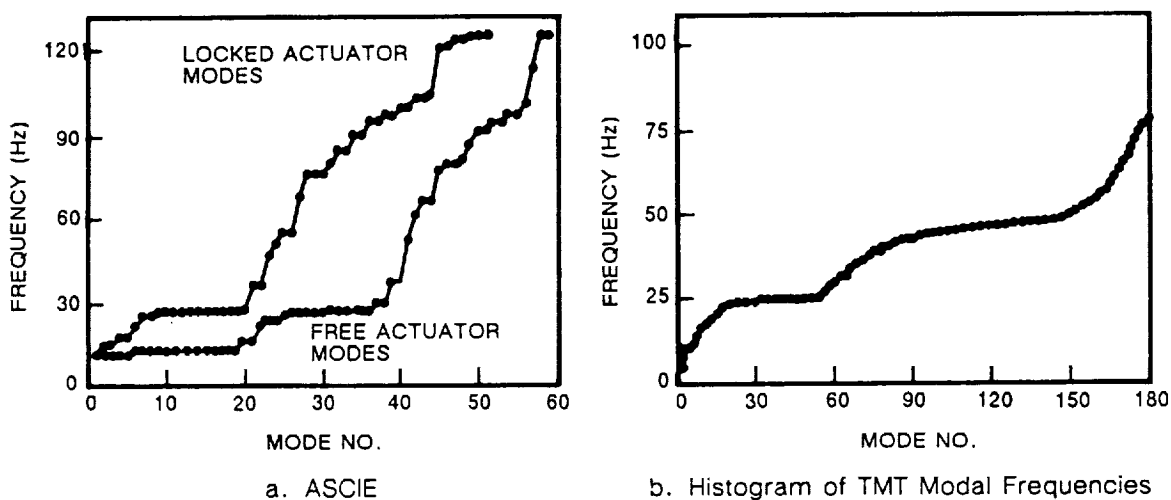


Figure 2

ASCIE STRUCTURE DYNAMICS PROPERTIES

The ASCIE structure was designed to replicate the complex dynamic behavior that characterizes large segmented systems. Typical of such systems is the modal grouping due to the high degree of symmetry of the structure. For a perfectly rigid support structure, the segments and their supporting mechanism (e.g. subcell and actuators) have almost identical dynamic properties and thus can be viewed as N identical oscillators at the same frequency. For ASCIE 18 modes of vibration related to the segments will occur at more or less the same frequency. However, because the support structure is in reality quite flexible, coupling between the grouped oscillators produces two results. First, the resonant frequencies tend to spread slightly by moving away from each other [Ref 7]. The second, and more significant effect in terms of CSI, is the creation of global, or collective modes in which the segments as a whole behave as a continuous sheet rather than as individual pieces. These modes effectively couple one part of the mirror to another, creating adverse interactions that did not exist when considering individual segment dynamics. Fig. 3 shows a comparison between the modal frequency histograms of ASCIE and of the Keck telescope. A great similarity can be observed. This behavior is quite different from that of a beam-like structure as also shown on the figure. In addition the ASCIE structure was tuned to have its significant modes around 12-15 Hz to be relevant to larger systems.



c. Cantilever Beam
Figure 3

COMPARISON WITH KECK TELESCOPE

Table I below shows a comparison between the principal parameters of ASCIE and the Keck telescope. Although of considerable difference in weight and size, the modal frequencies and the overall performance are very similar. With 18 actuators and 24 sensors, the control system is complex enough to be a valid test bed for the type of problems found in larger systems.

	ASCIE	KECK
PRIMARY MIRROR DIAMETER	2 m	10 m
NUMBER OF SEGMENTS	7	36
SEGMENT DIAMETER	0.6 m	1.9 m
NUMBER OF ACTUATORS	18	108
NUMBER OF EDGE SENSORS	24	168
TOTAL MASS	75 Kg	200,000 Kg
FIRST MODE FREQUENCY	7.2 Hz	5 Hz
FIRST CRITICAL MODE FREQUENCY	12 Hz	18 Hz
EXPECTING PHASING ERROR	30 nm	30 nm
EXPECTED TILT ERROR	0.1 arcsec	0.03 arcsec

Table I

ASCIE CONTROL SYSTEM PRINCIPLE

The segment alignment control system is similar to that of the Keck telescope. It utilizes a self-referenced system of edge sensors providing a set of error signals that are processed through a special algorithm to obtain the piston and tilt errors for each individual segment. Corrections based upon these errors are applied, through proper electronic compensation, to the actuators controlling position and tilt of each segment (Fig. 4). In such a centralized control system where the actuators are driven by signals from all the sensors, structural dynamics can couple back the actuators to all the sensors through global modes of vibration, thus resulting in potential instability.

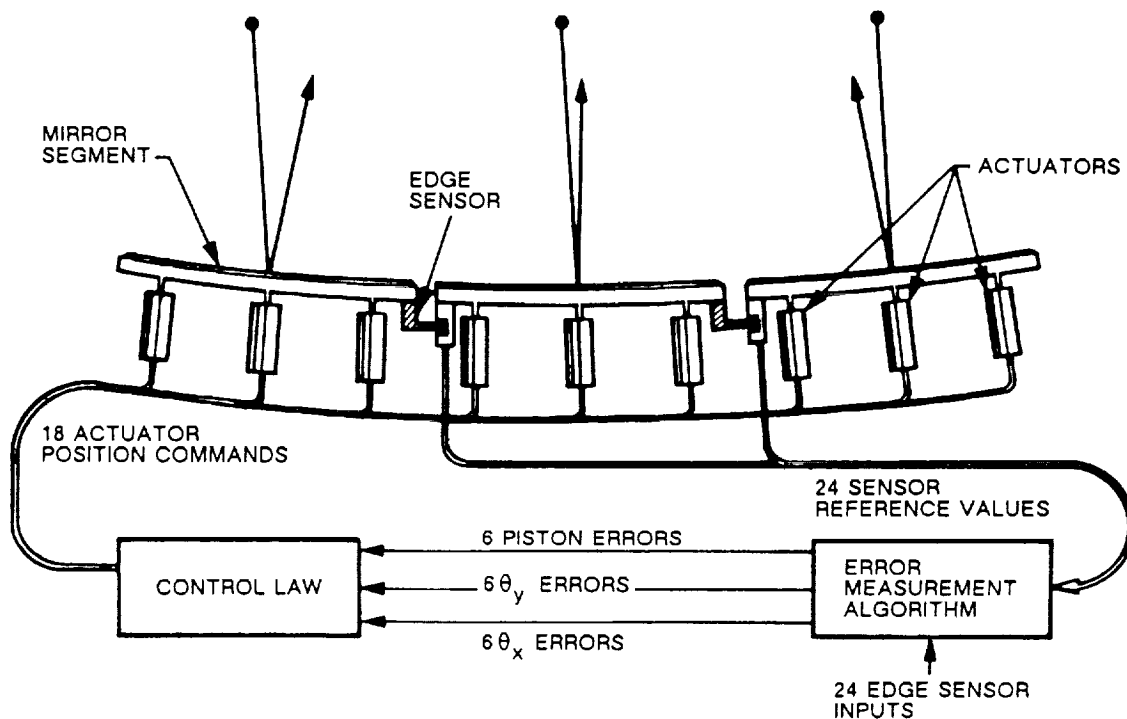


Figure 4

ASCIE EDGE SENSOR SYSTEM

The edge sensors used for ASCIE are small inductive position sensors as shown in Fig. 5a. This type was preferred to the capacitive sensors used for the Keck telescope because of their commercial availability, price and performance characteristics. Also they are very rugged and easy to use. The sensors are mounted on tabs attached to the segments, thus directly measuring the relative edge displacement. Each segment is surrounded by six sensors (2 per edge) as shown in Fig 5b. The offset from the true edge is a very important factor for the full observability of the system and it must be optimized in order to obtain the best sensitivity and noise performance. The redundancy (24 sensors to measure 18 degrees of freedom) also helps to reduce noise, is important for reliability, and will permit fault detection and accommodation studies. Since these measurements are relative, a reference must be chosen to relate them to the absolute axis of the telescope. In ASCIE, the central segment is taken as the reference.

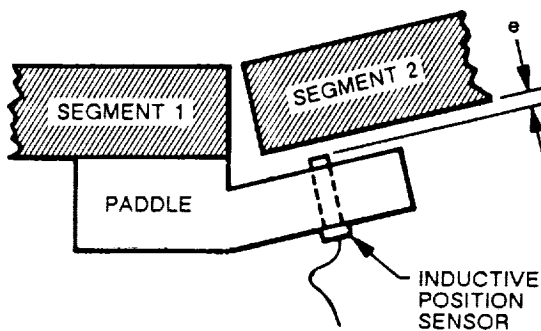


Figure 5a

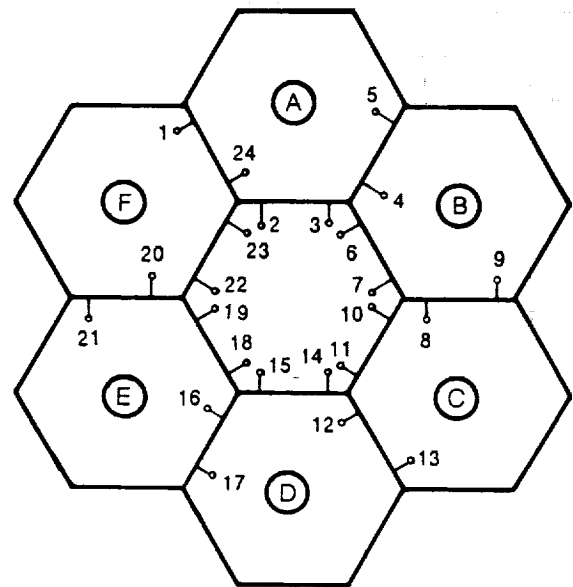


Figure 5b

ASCIE OPTICAL CALIBRATION AND SCORING SYSTEM PRINCIPLE

Fig. 6 shows the principle of an optical system that directly measures the tilt errors associated with each segment. It emulates a more complex wavefront sensor based on holographic patches, for example. The laser beam coming from the central tube reference is split into six equal beams by a special faceted secondary mirror. Each of the beams reflects on a small flat mounted on the corresponding segment reflects back on the same facet of the secondary mirror and finally focuses on a two-axis photodetector. The photodetector provides two electrical signals directly proportional to the position of the laser spot in two orthogonal directions. This optical system has a sensitivity of 0.1 arcsecond and is used to initially align the segments. After this operation the control system remembers the set points of all the edge sensors and maintains them in the presence of disturbances. The optical system is not a part of the control loop but can be used as an independent scoring system to evaluate the performance of the segment alignment control system.

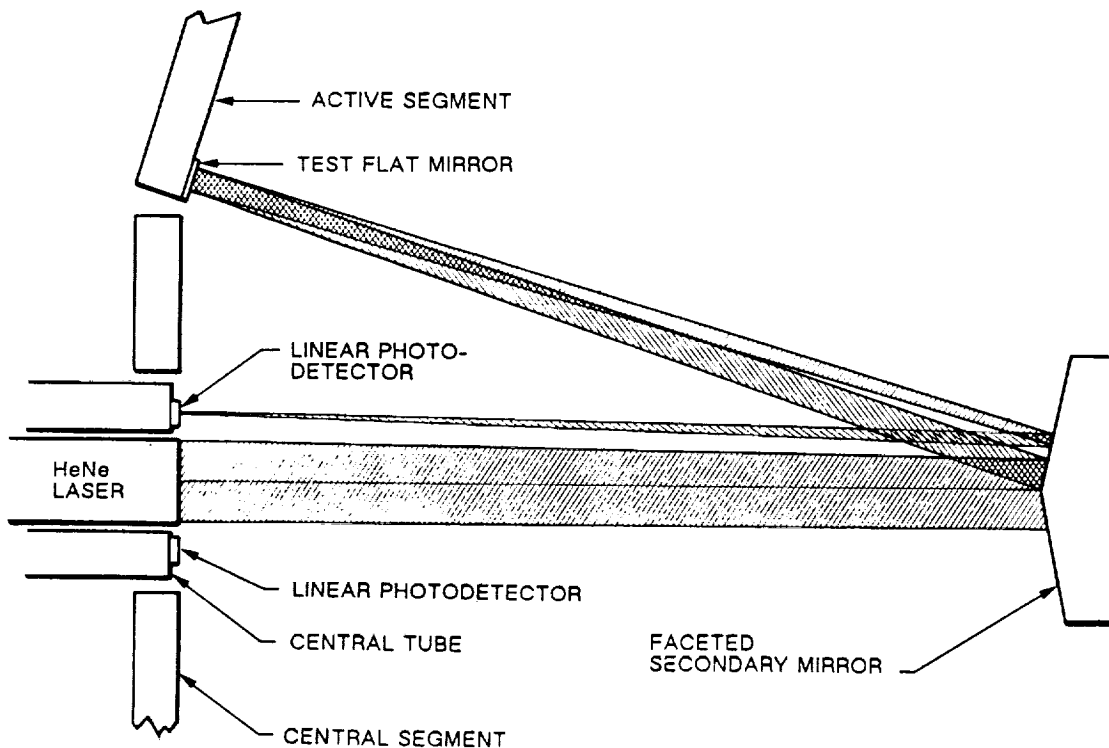


Figure 6

ASCIE DATA ACQUISITION AND CONTROL SYSTEM

The ASCIE system is shown schematically in Fig. 7. The central part is an electronic interface and control console. It contains the analog electronics that controls the actuators and conditions the signals from the sensors. It sends the conditioned edge sensor signals to the Array Processor (A/P) where the segment alignment control laws are implemented. This interface electronics can be operated directly or through a Personal Computer (PC). The PC has also a two-way communication system with the host processor (HARRIS-800). The host processor is used to perform control design, analysis, and data processing, and to control the A/P (downloading control gains, acquiring data from the sensors, the command channels and the internal states of the A/P, and starting and stopping the A/P). In addition to controlling the operations (automated procedures are implemented to power up or shut down the system, to establish various control modes, etc.), the PC is used to display all the important variables involved in the segment alignment control, i.e., edge sensor signals, commands to the actuators, and actual tilt and piston errors for each segment. This display gives the operator a complete view of the system operation and performance.

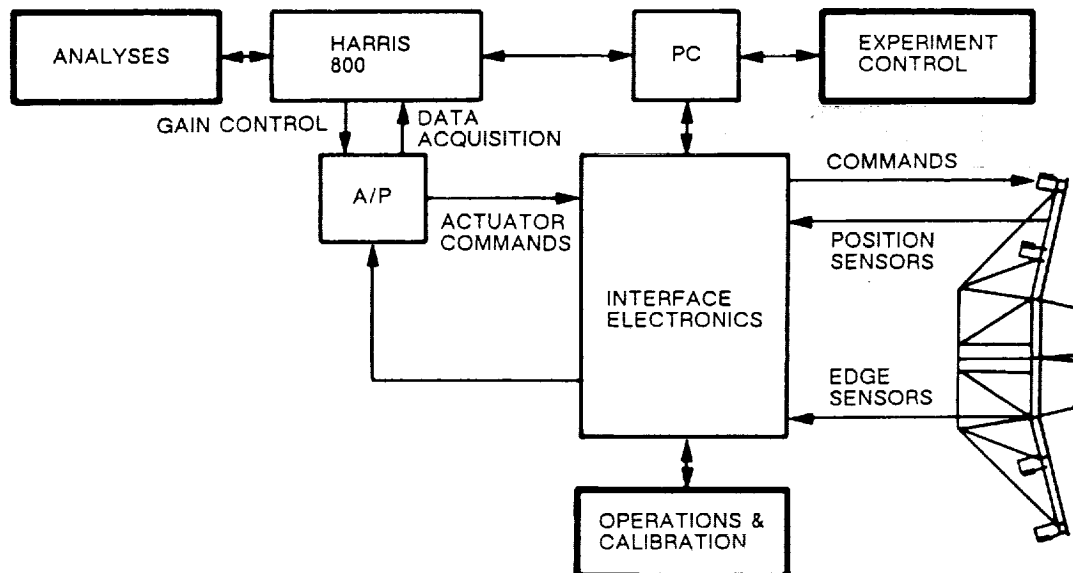


Figure 7

ASCIE HARDWARE

Fig. 8 is a view of the actual ASCIE hardware showing the active secondary mirror on the left, the focal plane sensor mounted in the center of the primary mirror, the small flat mirrors attached to the six peripheral segments near the central segment, and the truss structure supporting the segment actuators. These actuators were specially design in the Lockheed Palo Alto Research Laboratory and have a range of ± 1 mm with an rms noise of 30 nm. They contain a position servo-loop and are capable of running at a bandwidth greater than 100 Hz. The segments are directly attached to the actuators by special flexures that passively constrain lateral and rotational motions but allow the actuators to position them in the remaining three degrees of freedom (piston and tilts). In its present configuration the structure is cantilevered from the back of the central tube, but can be mounted either horizontally (as in the photograph), or vertically.



Figure 8

ASCIE PRELIMINARY TEST RESULTS

The objective of the experiments conducted at the Lockheed Palo Alto Research Laboratory is to predict and demonstrate the CSI phenomenon, and develop and test new control approaches to circumvent this problem. One of the main objectives of this research is to obtain results traceable to actual systems. Thus it was essential to design ASCIE for a level of performance comparable to that of optical systems. Preliminary tests were conducted by closing the loop on one segment, while the five others were passively restrained by their own actuator/flexure system.

The loop was closed successfully at a 5 Hz bandwidth. Preliminary analyses had indicated that with the simple integral control scheme used in this case, the CSI effect will limit the bandwidth to about 11 Hz. The traces shown in Fig. 9 are the actual displacements of the three control actuators while the loop is closed on the edge sensors. This 5-second run shows 300 nm (about 1/3 of a micron) motion due principally to thermal distortion in the support structure (the experiment was conducted in a typical laboratory environment). The actuator motions were commanded by the control system so as to maintain the correct alignment of the controlled segment with respect to its neighbors at all times. The corresponding piston and tilt errors are shown in the next plot (Fig. 10).

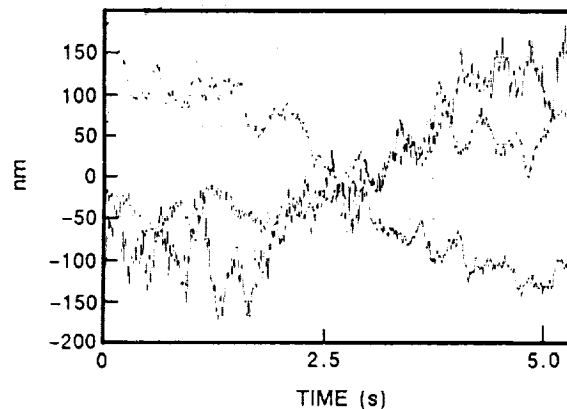


Figure 9

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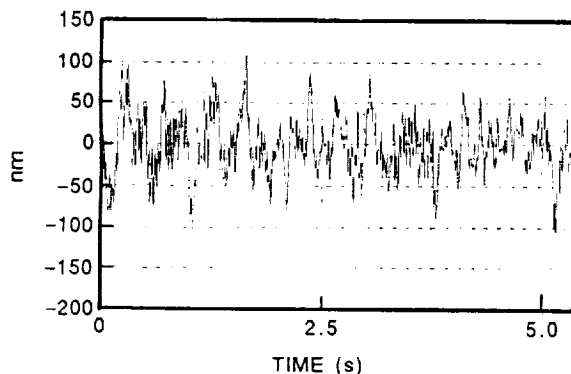
ASCIE SINGLE SEGMENT ALIGNMENT TEST (PISTON AND TILT ERRORS)

The segment alignment errors during closed-loop operations are shown in Fig. 10a for piston, and in Fig. 10b for the two tilt axes ("Petal" denotes a folding motion of the segments toward the optical axis). The residual error is due essentially to seismic and sensor noise. By contrast with the previous plot, the traces are here perfectly centered, i.e., the thermal drift has been completely eliminated. The level of performance that has been achieved (about 30-nm rms in piston and less than 0.05 arcsecond in tilt) is comparable to that of the Keck telescope requirements and thus represents a major step in validating the technology for large flexible segmented optical systems.

CONCLUSIONS

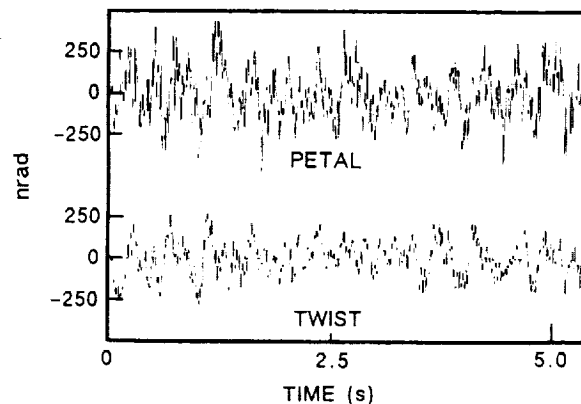
This paper has presented a description of the ASCIE experimental setup, a generic test bed for several essential technologies. In particular its multi-input, multi-output, non-collocated control system and its complex structural dynamics, characteristic of large segmented systems make it an ideal test bed for CSI experiments. The high accuracy of its measurement system will make it possible to investigate the dynamics of microvibrations and its implication for the CSI phenomenon.

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Piston error

Figure 10a



Tilt error

Figure 10b

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